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Conversion of lowland river flow kinetic energy

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ABSTRACT

This paper presents the analysis of possibilities and feasibilities of the extraction of kinetic energy from lowland rivers, which are slow and shallow and their water may contain organic fibres of water vegetation and solid particles of soil. In these rivers the existing hydrokinetic energy converters are not optimised for use because at small flow velocity the efficiency of such converters is very low. The depth of a shallow river flow may be not deep enough to install the converters. The latter are sensitive to jamming by water plant fibres. To overcome the difficulties in developing river flow kinetic energy the structures, the advantages and disadvantages of commonly used converters have been analysed A conveyor type converter has been found to be the most suitable for use in shallow rivers. Results of our field and laboratory studies of hydrokinetic energy converters have confirmed the anticipated difficulties when applying the commonly used converters in lowland rivers. The validity of our proposed method has allowed to reduce the number of mobile elements and friction couples in our novel converter and to increase its reliability. A particular approach to the principle of kinetic energy extraction from a river flow has been developed and a novel converter has been invented. To increase the efficiency of the river flow kinetic energy conversion a new conveyor technology has been proposed. This converter allows the extraction of kinetic energy from the river flow almost without affecting the river and the surrounding environment.

Contents

1. Introduction

The possibility to extract energy from a river flow without the construction of a dam, the arrangement of a pond and flooding of a valley make kinetic energy of flowing water a very attractive energy source. For this reason, the interest in river flow kinetic energy is currently increasing, but until recently its technological deployment has been negligible [1,2]. The majority of publications

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about the possibilities of water flow kinetic energy development examine marine systems [3,4] and only a few of them examine river systems [5,6]. The authors of some publications analyse both marine and river technologies and the equipment applied [7,8], but almost nobody has studied the peculiarities of the development of lowland river kinetic energy.

A vertical cross flow turbine was tested in a deep (6–7 m) Swedish river site with the velocity ranging between 0.4 and 1.4 m/s in order to prove the concept, to validate the simulation tools and gain experience in operating the unit in various conditions [9].

To facilitate the design of axial hydrokinetic turbines, a numerical method for the analysis of their operating conditions was developed based on a series of laboratory tests [10]. The shape of a similar type turbine was designed by CFD, then its model (rotor diameter of 150 mm) was tested in a wind tunnel and a prototype (rotor diameter of 1 m) was installed in a river in Germany [11].

A series of tests on several Darrieus type cross flow hydrokinetic turbines were conducted by mounting each turbine in front of a barge and motoring through still water at a speed ranging from lower than 1 m/s to up to 5 m/s [12]. Differences in the coefficient of the performance of a number of turbine configurations ranging from lower than 0.1 to 0.25 were revealed, while the turbine associated with ducts could increase the coefficient by a factor of 2 or 3 and, consequently, the power output too.

A specific floating energy converter, containing an in-plane axis cross flow turbine, which can be used in shallow rivers, was designed with a purpose to utilise the streams with slow flow velocities (down to 1.0 m/s); its laboratory experiments and field tests were performed [13]. Impacts on the flow velocity, backwater, changes in the river morphology were revealed and the measurement results were used as the input data for a 3D numerical model to simulate the power output as well as further impacts on the environment.

Numerical modelling of a fixed pitch cross flow hydrokinetic turbine to maximise its performance and smooth operation was carried out by Lazauskas and Kirke [14].

A river is rather sensitive to human activity. Sustainability and possibilities to develop kinetic energy of a river without damming it and with minimal impact on the environment are recognised as significant advantages. It should be accepted that kinetic energy is not intensively distributed in the river flow. Its level determines the ease of using the energy of this type in practice.

Let us consider this kind of kinetic energy and try to estimate the real possibilities of utilising this energy source for human needs. Currently, as rivers have become strictly protected by ecologists and environmentalists from any disruption, any obstacle in the fish migration path is considered to cause harm to the environment. Here, we will analyse the real intensity of kinetic energy in lowland alluvial river flows and the possibilities of converting and utilising it for our needs.

2. River flow kinetic energy

An approximate magnitude of river flow power P is expressed by the following simple well known formula:

$$P = \rho g Q H, \qquad (1)$$

where $\rho = 1000\ \text{kg/m}^3$ is water density; $g = 9.81\ \text{m/s}^2$ is acceleration of gravity; Q is flow discharge; and H is pressure head. Last parameter H is used to express relative power in units of length, and it consists of relative potential and kinetic energies, i.e.

$$H = h + \alpha v^2/(2g) \qquad (2)$$

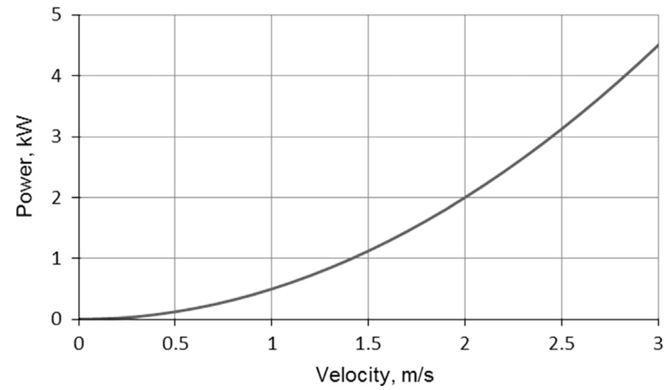

Fig. 1. P–v plot for $Q = 1\ \text{m}^3/\text{s}$.

here, h is flow depth (potential energy); $\alpha v^2/(2g)$ is velocity head (kinetic energy), where α is Coriolis coefficient and v is mean flow velocity. These two parts of energy are closely inter-related. An increment in flow velocity v leads to a decrement in both flow depth h and the cross-sectional area.

Expressing river flow discharge $Q = Av$, where A is the area of the river flow cross section, and assuming that $\alpha = 1$ in $H = \alpha v^2/(2g)$, Eq. (1) takes the following form of kinetic energy power:

$$P = 0.5 \rho Q v^2 \qquad (3)$$

or

$$P = 0.5 \rho A v^3 \qquad (4)$$

When the dependence of kinetic power on velocity is analysed, it should be taken into account that at Q=constant any change of velocity v causes the change in flow cross-sectional area A. Therefore, it is more correct to use the quadratic Eq. (3) instead of cubic Eq. (4) P–v relationship for the analysis and illustration of kinetic energy resources. A rapid increase in kinetic energy occurs with the growth of velocity due to its quadratic relationship with velocity in Eq. (3). This is shown in Fig. 1, where the P–v relationship graph is given for $Q = 1\ \text{m}^3/\text{s}$=constant Similar plots, primarily in the form of power density (kW/m^2), are used to illustrate the promising future of the use of kinetic energy sources [1,15], but in these cases Q=var. A potentially large amount of power from kinetic energy promise bright future for the development of river kinetic energy sources. We will consider what type of the development of kinetic energy sources can be actually achieved.

The value of 4.5 kW for each m^3/s of water flow at velocity of 3 m/s is a very good power concentration. However, other issues should be considered before determining the potential development of kinetic energy sources. Let us analyse water flow velocities in lowland alluvial rivers.

The river flow velocity never exceeds non-scouring velocity of the soil forming the river bed. If this condition is violated, bed scour and river meandering begin. It proceeds until the length of the river has sufficiently increased and its hydraulic gradient and velocity have decreased to restore the equilibrium in the interaction between the water flow shear action and the resistance of a river bed to that shear. The mean water flow velocity in alluvial rivers usually varies within the range of 0.3–0.8 m/s and seldom exceeds 1.0 m/s.

The stream velocity in the middle of the river may reach up to 1.5–2.0 m/s; however, such high velocities occur during spring or storm floods and last only for some days or even hours. Thus, in the analysis of the lowland river flow kinetic energy resources their velocities should be considered not to exceed 1.5 m/s.

Table 1
Kinetic power dependence on the flow velocity of a river with a flow rate of $Q=1\text{m}^3/\text{s}$.

v (m/s)	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
P (kW)	0.020	0.080	0.18	0.32	0.50	0.72	0.98	1.28	1.62	2.0
P_c (kW)	0.0022	0.0088	0.020	0.035	0.055	0.079	0.11	0.14	0.18	0.22

Kinetic energy power P for velocities <1.5 m/s is so small that it is difficult to determine on the graph (Fig. 1). Therefore, some magnitudes of the power are listed in Table 1.

To extract whole power P listed in Table 1, the flow must be completely stopped, regrettably, that is not possible. Under the action of gravity forces the flow should be allowed to flow further downstream of the converter with its parameters unchanged and in line with the river bed conditions and its slope.

Definite uplift of the flow upstream of the converter is unavoidable. The uplift is the potential energy whose magnitude is equal to kinetic energy extracted from the flow and lost due to hydraulic loss. The uplift magnitude depends on both the ratio of the flow cross section to the converter areas and the flow rate. According to our field investigation data the uplift of the water level upstream of the converter varies from parts of a millimetre to some centimetres and even more.

The approximate magnitude of the power from the converter may be computed by the following formula [16]:

$$P_c = F_c v_c \eta_c, \tag{5}$$

where F_c is force of hydrodynamic pressure of the water flow to the working element of the converter; v_c is velocity of the element motion; and η_c is overall converter efficiency (or power coefficient) which is equal to the product of hydraulic and mechanical efficiencies η_h and η_m, i.e.

$$\eta_c = \eta_h \eta_m. \tag{6}$$

The efficiency of converter η_c is a parameter of great importance, so much so that it is rather small and is a limiting index that determines whether the final solution develops definite river kinetic energy. Some attempts to develop theoretical formulas for the computation efficiency of converters are known [6,17]. Unfortunately, they neglected the law of motion quantity for a flow deflection phenomenon. Nevertheless, interesting and useful results were achieved. These formulas may be used only to obtain approximate magnitudes of the converter efficiency. Experimental magnitudes of the efficiency as a rule are smaller.

It is commonly known that hydrokinetic energy conversion systems show a lower efficiency coefficient. Typical overall efficiency of river flow kinetic energy converters varies within the limits of 0.10–0.35. The measures for increasing the performance coefficient have been proposed in [12,18].

Hydrodynamic pressure force F_c that acts on the working element of a converter [19] is expressed by the following formula:

$$F_c = \eta_h \rho A_c (v^2 - v v_c), \tag{7}$$

where

$$\eta_h = \frac{\int_A (u^2 - u v_c)(1 - \cos \beta) dA_c}{(v^2 - v v_c) A_c} \tag{8}$$

where, η_h is hydraulic efficiency; A_c is cross-sectional area of the flow stream under the influence of the converter; v is velocity of the water flow averaged along surface A_c; v_c is velocity of the motion of a converter's working element; β is flow declination angle; and u is local water flow velocity at a definite point of area A_c.

Efficiency η_h depends on the characteristics of distribution of velocity u along surface A_c, the relationship between velocities v and v_c and declination angle β. In the case when $A_c \ll A$, an assumption may be made: $u=v=\text{constant}$ and $\beta=\text{constant}$. Then, Eq. (8) becomes the following:

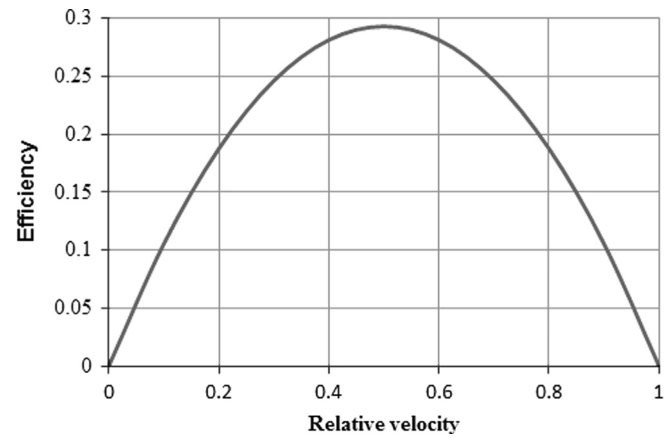

Fig. 2. Graph of theoretical relationship $\eta_h-(v_c/v)$.

$$\eta_h = (1 - \cos \beta). \tag{9}$$

In the open flow $\beta < 90^\circ$. Thus, according to Eq. (9) $0 < \eta_h < 1$, which corresponds to reality. The situation of $\beta = 90^\circ$ is only possible at the centre of, say, a flat vane. Moving from that point towards the perimeter of area A_c, flow declination angle β reduces from $\beta_{max} = 90^\circ$ to $\beta_{min} = 0^\circ$ at the line of the perimeter of area A_c. As a result of the integration according to Eq. (9), the average magnitude of β will be between 0° and 90°, say, $\beta_a = 45^\circ$, which corresponds to $\eta_h = 0.293$.

Mechanical efficiency expresses a relative loss of energy due to mechanical friction between the elements of the converter. The amount of friction loss depends on the structure of the converter and its working regime. It is easy to determine the loss when the converter is stopped and also when it works with a free shaft. However, at intermediate regimes, the measurement of the loss is problematic. Nevertheless, we investigated the mechanical energy loss both in the field and under laboratory conditions and found them to be rather large and prevalent for determining of η_c. It varied within a wide range from 0.05 to 0.30.

When $v_c = v/2$ the converter works in the optimal regime [16]. According to this regime and Eqs. (7) and (5) the power developed by the converter acquires the following expression:

$$P_c = \eta_c \rho A_c v^3 / 4. \tag{10}$$

Accepting that hydraulic and mechanical efficiencies are $\eta_h = 0.293$ and $\eta_m = 0.75$ respectively, the overall efficiency coefficient obtains magnitude $\eta_c = 0.220$. Hydraulic efficiency, in its own turn, depends on the ratio of velocities v and v_c (Fig. 2) [16].

Assuming that the entire cross section of the river is occupied by converter ($A_c = A$), and its resulting power P_c is expressed by Eq. (10) compared to river kinetic energy power P which is expressed by Eq. (4), we determined that only 1/9 of the river flow kinetic power may be extracted by the converter under optimal conditions. Approximately, the same ratio (1/9) was accepted during the estimation of the river kinetic energy potential in the USA [20].

To assume better quantities of the energy available for extraction from the river we accepted constant flow rate $Q = 1\ m^3/s$. The magnitudes of flow kinetic energy power P and power P_c developed by the converter have been computed by Eqs. (3) and (10), where $vA_c = Q$ (Table 1).

A big difference between converter's power output P_c and river flow kinetic energy power P may be explained by the following reasons:

- impossibility to reduce the open water flow from the initial direction of motion by more than 90°;
- comparatively (with respect to small kinetic energy) large mechanical and hydraulic energy loss due to converter's low efficiency;
- slow velocity and shallow flow of lowland rivers.

The ways to overcome the difficulties stated above will be described below.

3. Peculiarities of lowland rivers

The bed of a lowland river is usually formed of alluvial soil. The resistance to scour of such soil is rather low. When the flow velocity increases and reaches the critical magnitude, the bed scour starts.

Critical velocity for non-cohesive soils (sand, gravel, cobbles) depends on the grain size and varies within the limits from 0.3 m/s to 2.0 m/s. For cohesive soils (loess, loam, clay) critical velocity varies within the limits from 0.5 m/s to 1.5 m/s. These velocities are the limits of the possible maximal velocities of the river stream, which may occur during floods in a definite reach of a river with a high slope.

Long lasting bed scour causes large scale bed deformations and even meandering of the river. As a result, the river length increases, its slope decreases, the flow velocity and kinetic energy reduce. Nevertheless, a short-term increment in the kinetic energy potential should not mislead us. Velocity of 1.5 m/s should be accepted as the maximum velocity of the lowland river kinetic energy parameter. For Lithuanian rivers, to estimate their kinetic energy potential the maximal velocity should be accepted of the level of only 1.2 m/s. In addition, it is the limiting velocity that determines the maximal possible power of the converter. The limiting velocity is higher than that justified economically and technically. The justified velocity should be determined from the plot of the velocity distribution in time (Fig. 14), which may help to achieve a high degree of utilisation (or a capacity factor), while a low ratio of the maximum to the rated velocity is preferred. According to Lalander et al. [21], in Sweden the ratio of the maximum to the rated velocity proposed is less than 2.0 m/s, 1.2 m/s, and 1.6 m/s for regulated rivers, unregulated rivers and tidal currents, respectively.

The broad and shallow cross sections of the flow is another important peculiarity of lowland rivers. The shallowness of the flow creates special demands for the structure and dimensions of the converter. The shallow flow and its low velocity create good conditions for water vegetation to flourish. These water plants reduce water velocity, occupy part of the flow and fill the river with organic fibres. It is well known that some kinetic energy river deployments experience major problems with debris attaching to the turbines, resulting in the failure of the system. Excessive work in cleaning of racks results in frequent power outages. Some methods of dealing with the water plant problem have been suggested, and mitigation measures that do not involve lifting the turbine out of the water have been proposed [22].

As indicated previously, the above mentioned conditions result in special requirements for the converter's type, structure and dimensions, which should be taken into account before making a decision about the possibility to utilise river flow kinetic energy by selecting the type of the converter and performing the design work.

4. Kinetic energy converters

Of all the mechanisms used for the conversion of river flow kinetic energy we are inclined to divide them into rotary and conveyor-type machines. Rotary type machines are more prevalent than conveyor-type ones. According to the position of the working element axis we divide the rotary-type machines into those with vertical and horizontal axes.

The schemes of the indicated machine types are shown in Fig. 3. The advantage of rotary motion machines is a small number of mobile elements and friction couples contacting with water. They may contain organic fibres and soil particles. Aquatic plants may jam the openings of the converter, solid particles may erode and spoil working surfaces of friction couples.

Primitive rotary converters called water wheels with a horizontal axis (Fig. 4) known from ancient times are currently used in Lithuania [23] and other European countries.

Some arrangements of water wheels are shown in Fig. 4. Water wheels are simple and reliable but clumsy and inefficient. Currently these rotors are the remnants of the cultural heritage, artefacts or reminders of the past.

The indicated shortcomings of a water wheel are offset by the possibility of using the machine in the shallow flow. In fact, the width of the converter vanes may be adjusted in such a way as to cover almost the entire cross section of the stream. The distance of some centimetres from the end of the vanes to the bottom of the

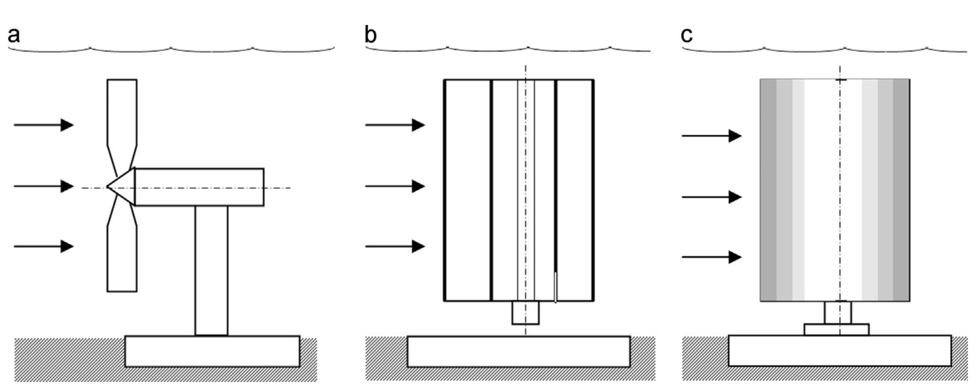

Fig. 3. Schemes of rotary converters with horizontal (a) and vertical (b), (c) axes of the rotor.

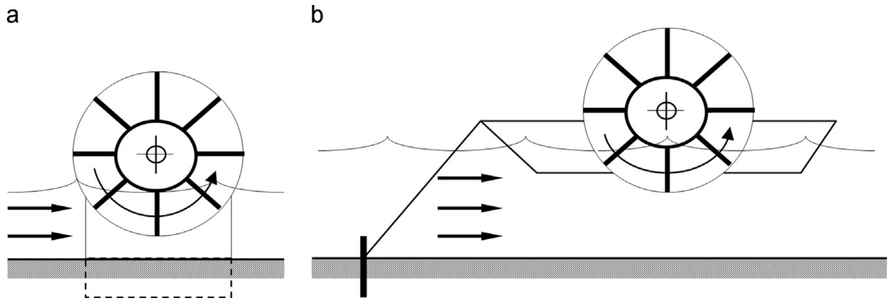

Fig. 4. Water wheels with foundation (a) and boat support (b).

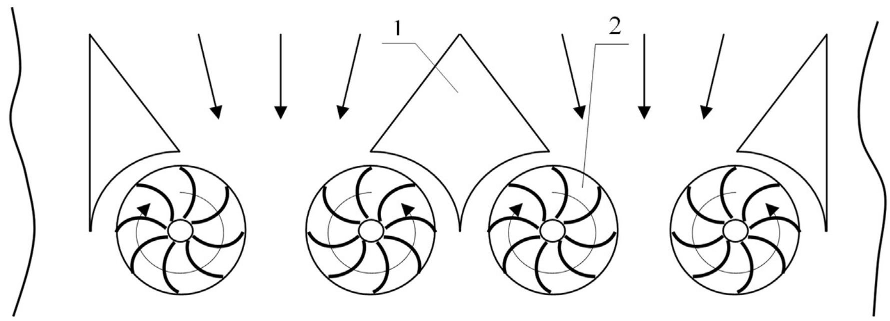

Fig. 5. Layout of vertical axis converters (view from the top) [25] 1 – deflector; 2 – vertical axis turbine.

Table 2
Power P_c (in W) developed by rotary type converter with a horizontal axis.

v (m/s)	Diameter of the converter's runner, D_p (m)				
	0.5	1.0	2.0	3.0	5.0
0.5	1.349	5.40	21.6	48.6	134.9
1.0	10.79	43.2	172.7	389	1079
1.5	36.4	145.7	583	1311	3640
2.0	86.4	345	1382	3110	8635

river or the flume is sufficient to avoid the contact with the bottom of the river.

A modern rotary converter with a working element of a propeller type [1,7,8,24] has much smaller dimensions and a higher efficiency than those of a water wheel, although it has a rather large relative mass (kg/kW). An increase in the power of the converter leads to reduction in the relative mass of the unit. An increase in the number of power units (Fig. 5) has no effect on the efficiency and relative mass of converters.

A rotary converter with a runner and a horizontal axis requires a considerable depth of the water flow exceeding the runner's diameter. The power developed by the converter is proportional to area A swept by the rotor. The power may be computed by Eq. (10), where efficiency η_c should be accepted according to the type of the runner.

Let us compare the wind and water flow kinetic energy converters. A brief comparison of the wind and hydro turbines concerning the energy capacities of these systems is given by Khan et al. [7]. Water density ρ is 770 times greater than that of air, but velocity of motion v is approximately 10 times smaller than that of air. The power of velocity in Eq. (10) is 3; therefore, it is possible to understand that the wind and water kinetic energy converters of the same diameter would be approximately of the same power. But the conditions to use rotors of a large diameter either in the atmosphere or in the water differ. Some magnitudes of the propeller type converters with horizontal axes are computed by Eq. (10), assuming efficiency η_c=0.22 listed in Table 2.

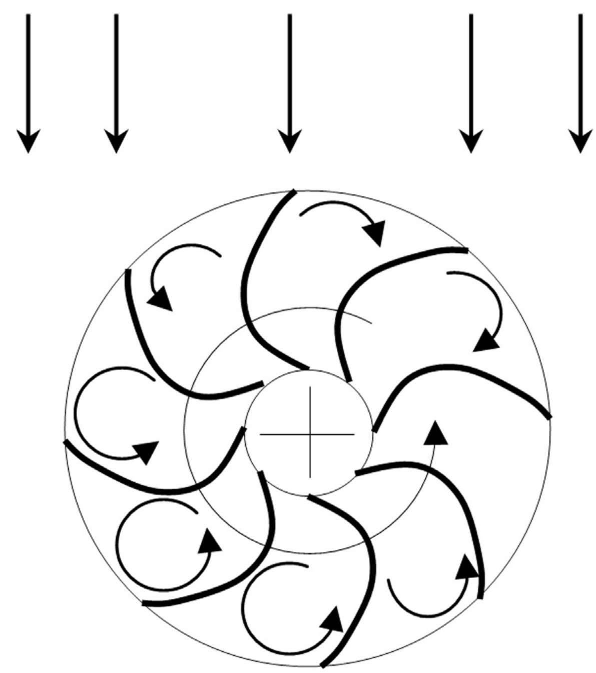

Fig. 6. Scheme of the vortexes in a rotational converter with a vertical axis.

Again we may see rather limited possibilities of the lowland river kinetic energy converters of a rotary type. If river depth h=1.2 m and rated flow velocity v=1 m/s, the converter D_p=1 m may be used and only maximal power P_c=43.2 kW may be achieved.

The requirements for a significant depth of the flow for placing rotary converters may be considered as a shortcoming of such machines. Despite this indicated shortcoming, the rotary converters are useful when the flow is sufficiently deep, e.g. under marine conditions and when water is free of fibres. It is evident from Table 2 that a rotary-type converter with a propeller is not

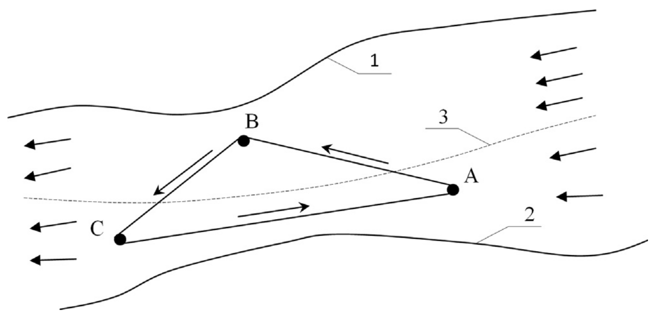

Fig. 7. Scheme of conveyor type converter: 1 and 2 are river bank lines; 3 is *talweg*; *A*, B, C are mooring posts; AB and BC are working parts of a steel cable with open vanes; AC is return part of the cable with closed vanes.

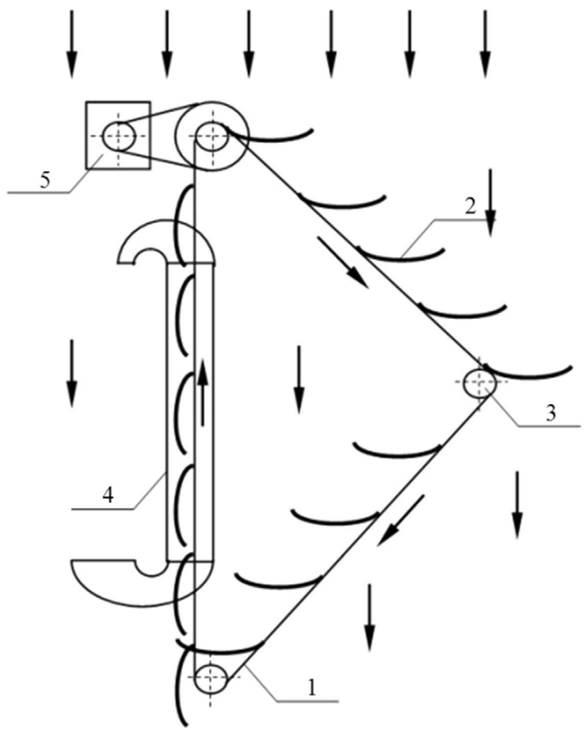

Fig. 8. Conveyor-type converter with a covered return part of the working element [28]: 1 is steel rope; 2 is vane; 3 is mooring point; 4 is protecting cover; and 5 is electric generator.

suitable for shallow (depth $h \leq 1$ m) rivers or for slow ($v \leq 1$ m/s) water flows.

Rotary converters with vertical axes are less efficient compared to those with horizontal axes. Both working and returning sides of the rotor are inside the flow and are acted upon by the flow. A considerable amount of energy extracted by the converter is consumed to speed up and slow down vortexes between the vanes of the runner (Fig. 6). Stream deflectors 1 in front of turbines 2 (Fig. 5) have an uncertain effect, which should be verified by special studies.

Some researchers [26] attempted to construct rotary converters with a vertical axis (Fig. 1c) acting on the basis of the Magnus effect [27].The Magnus effect is widely used in the field of wind power, where there is no fluid pollution problem. A large number of friction couples and moving elements raise some concerns about the validity of the idea of the indicated invention, as well as about some other proposed approaches [28–30], mainly for the same reasons.

The loop of a long flexible element, such as steel cable, chain, rope, or belt with vanes attached to it, is used as a working element of a conveyor-type converter [3]. One part of a conveyor-type converter performs the working motion in the form of a rest–return motion. Re-switching from working to return motion and vice versa occurs at definite mooring points of the loop (Fig. 7). Sometimes the vertical position of the converter loop is more convenient for power extraction, but such configuration requires much larger water depth.

The concentration of fibres and solid particles in water on the river bottom is higher than in the main part of the river flow; therefore, when a working element of the converter is close to the bottom of a river bed, the measures to protect the system from pollution should be taken with an adequate amount of efforts and attention. Protection of the return part of working element 1 of the converter (Fig. 8) by cover 4 is rather useful [28], but the cover itself may be clogged by trash; thus, the cover may require regular cleaning from trash, which may require many efforts and much time. The cover may reduce the resistance of the conveyor return forces and the hydraulic loss of energy.

In addition to protect against jam in a converter, reduction in the energy loss due to friction couples is the next rather important problem to be solved. Conveyor-type converters with chain drives (Figs. 7–9) are typical examples of the systems with a large number of mobile elements and friction couples [29,30]. Sensitivity to the presence of fibres in water makes mobile elements become unreliable; in addition, great losses of mechanical energy in friction couples counteract some of their advantages.

For conveyor-type converters, the requirements for an adequate depth of the flow are minimal. A depth slightly larger than the width of the vanes is well-suited to a normal operation of such conveyor-type machines. However, the structure of the working element and the system of energy transfer from it to the electric generator are rather complicated, as indicated in the following examples.

A converter with a long steel chain on the river bottom and vanes attached to it is shown in Fig. 7. The system is designed to operate at the sea bottom. The working part of the chain with the vanes is located diagonally to the stream; therefore the vanes do not interfere with each other. The return part of the chain is parallel to the stream, the vanes are closed and the resistance to the motion and the loss of energy is minimal [28].

The above-described systems are theoretically correct, but all of their structures are rather complex with a large number of mobile elements and friction couples making the reliability of the system problematic. All of the known conveyor-type converters [3,28–30] exhibit the same discrepancies and can be rarely recommended for use in lowland rivers. Despite these shortcomings, we have used them as the basis to start our investigation. For testing the machines in the field and in laboratory conditions we have

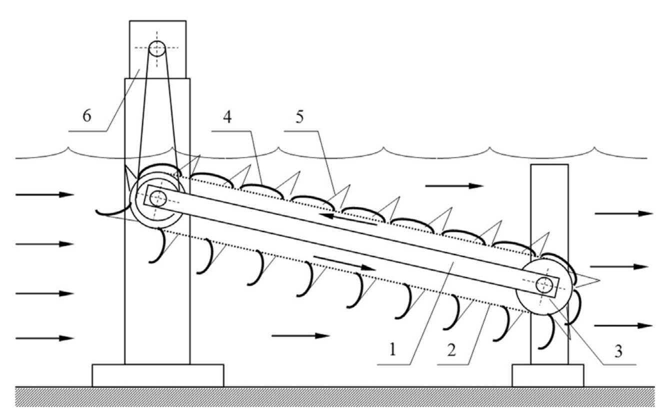

Fig. 9. Conveyor-type converter with twisting vanes [29]: 1 is beam; 2 is chain; 3 is sprocket; 4 is vane; 5 is support; and 6 is electric generator.

Fig. 10. Photograph of the operating power plant with four vertical axes converters. (see its layout in Fig. 5) [25].

Table 3
Results of the rotational motion converter tested in situ.

Test No	Velocity of the vane end (m/s)	Force at the lever end, F (N)	Torque (Nm)		Power (W)		Efficiency
			Real	Theoretical	Real	Theo-retical	
1	0.46	0	0	76.7	0	69.8	0
2	0	70	25.2	239	0	0	0
3	0.65	0	0	95.7	0	125.2	0
4	0.47	23	20.7	214	19.6	202.4	0.10
5	0.34	26	23.4	301	16.0	205.3	0.08
6	0.41	35	31.5	254	26.0	209.8	0.12
7	0.37	40	36	285	26.3	208.0	0.13
8	0.36	44	39.6	292	28.1	207.3	0.14
9	0.11	50	45	454	9.7	98.1	0.10
10	0.25	57	51.3	359	26.0	181.6	0.14

searched for the ways to eliminate the noted discrepancies of the machines and to improve their structure and characteristics.

5. Field investigation of converters

We have studied two river flow kinetic energy power plants operating in Lithuania. One of them is permanently installed on the Merkys River (catchment area $A=850\ \text{km}^2$, mean discharge $Q_o=8.0\ \text{m}^3/\text{s}$ and mean velocity $v_o=0.7$ m/s), and the other is a mobile power unit.

The first power plant consists of 4 rotary-type vertical axes turbines (Fig. 5) [25].The diameter of the rotor and its height are the same, i.e. 1 m (Fig. 10). All four converters of vertical axes turbines are connected by a common chain drive.

We measured the rotation speed and the torque developed by all four machines on the common shaft. The loading torque was changed from free rotation of the wheels down to their complete stop. To determine the torque, the claw of the brake was put onto the rotating axis, and the intensity of squeezing was adjusted while the force at the end of the brake lever was measured.The rotor speed was determined over the durations of 10, 5, or 2 full revolutions, as measured by a stop watch. The torque and power were computed from the measurement results and compared with their theoretical magnitudes (Table 3).

The differences between the real and theoretical magnitudes of the torque and power are evident. In all cases the real torque and power magnitudes are many (5–10) times smaller than the theoretical values.

Fig. 11. Installation of the conveyor-type converter for testing.

There are some possible reasons for this disagreement between the experiment and theory. Note that the river flow velocities change across the river. The stream of the flow was concentrated between the third and the fourth converters, while the first converter was in still water and was actually an energy consumer. The next and the primary reason was that converter's efficiency coefficient η_c in Eq. (5) and declination angle β in Eq. (8) in computation of theoretical torque and power magnitudes were enlarged and too optimistic. Thus, the tested machines exhibited very low efficiency.

Table 4
Results of the conveyor-type converter tested in situ.

Test No	Test conditions	Velocity (m/s)	Force (N)		Power (W)		Efficiency
			Real	Theoretical	Real	Theoretical	
1	H	0.35	0	288	0	101	0
2		0.26	31.3	346	8.1	90.0	0.09
3		0.31	39.1	314	12.1	97.2	0.13
4		0.24	70.4	358	16.9	86.0	0.20
5		0.22	93.9	371	20.7	81.6	0.25
6		0	133	512	0	0	–
7	I	0.35	0	288	0	101	0
8		0.26	39.1	346	10.2	90.0	0.11
9		0.22	66.5	371	14.6	81.6	0.18
10		0	93.9	512	0	0	–

Note: H and I denote horizontal and inclined orientations of the conveyor respectively.

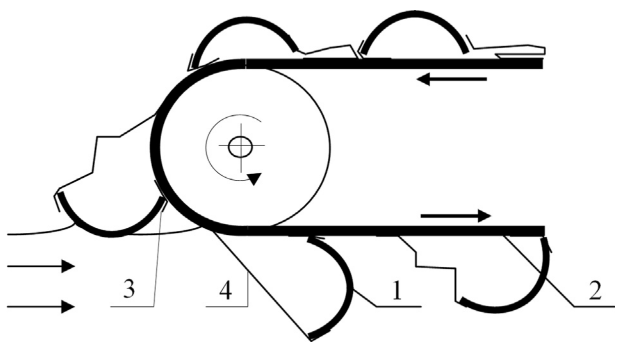

Fig. 12. Section of the working element of the modified converter model.

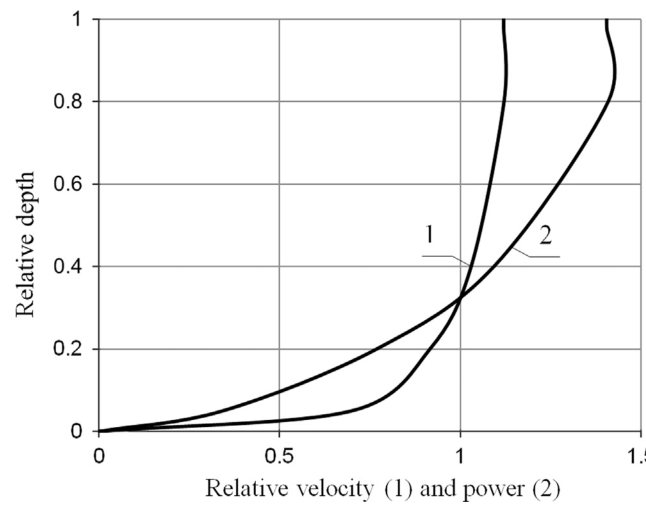

Fig. 13. Relative velocity (1) and power (2) versus relative distance from the river bed.

The installation of a conveyor-type mobile power unit by Bloze et al. (Fig. 9) on the Nemunas river is shown in Fig. 11. A similar technology of the rotor-type converter was used for the tests of a mobile converter. The test and computational results are described in Table 4. Again, big discrepancies are found between the real and theoretical magnitudes of the converter parameters. The same reasons for the differences may be also indicated here. In addition, the vulnerability of the tested converter was evident. The operation of the converter was interrupted many times during the test, most likely due to sand particles entering in flexible joints.

6. Laboratory investigation of converters

Models of the modified conveyor-type machine (Fig. 8) were constructed and used for our investigation. Because of possible corrosion of metal in water and jamming of converter joints we rejected the chain drive for its being unreliable and replaced it with a belt drive (Fig. 12). Hinge joints of vane 1 with belt 2 were replaced by short snippets of plastic tape 3. Tape and outhaul 4 were supple enough to avoid both the energy loss and the significant errors of investigation results.

The investigation was carried out using flat and semi-cylindrical vanes. The drag coefficients [31] of the vanes were determined using our newly developed method [32]. The determined magnitudes of the coefficient for semi-cylindrical vanes were approximately 20% larger than those of flat vanes [31].Thus, semi-cylindrical vanes are preferable. It is easy to make such vanes by cutting a pipe of the required diameter into two.

It is to be noted that during the experiments only the first open vane on the driving pulley works in full force. The next 2–4 vanes move chaotically with free outhauls (Fig. 12), which indicates their uselessness.

Our experiments were performed using two models of the working element. The distance between the vanes of one model was equal to their two heights and the distance of the other model was equal to three heights of the vanes. According to our observations the indicated distances were too small for the efficient operation of the horizontally located belt with the vanes. To determine the optimal magnitude of the distance, which definitely depends on the height of the vanes as well as on the velocity of river flow, special investigation should be done. The obtained results would help determine the optimal height of the vanes, the length of the belt, the diameter of the pulleys, the angle of belt inclination.

The water flow velocity and kinetic energy depending on it vary within the big limits across and along the river, also in time. It is commonly known that the greatest velocities are in the middle of the river and close to the free flow surface, while the smallest are at the bottom of the river. It is seen in Fig. 13 that the upper part of the lowland river flow to 60% of its depth constitutes 65% of flow rate Q and 73% of total kinetic energy [33]. Besides, the bottom layer of the flow should be avoided not only because of the low energy concentration, but also because of higher concentration of fibres and solid particles.

Velocity of the river flow is one of the most important parameters for the selection or design of a converter and for the computation of its energy production. The river flow velocity varies in time from maximal during the flood period to minimal during the summer

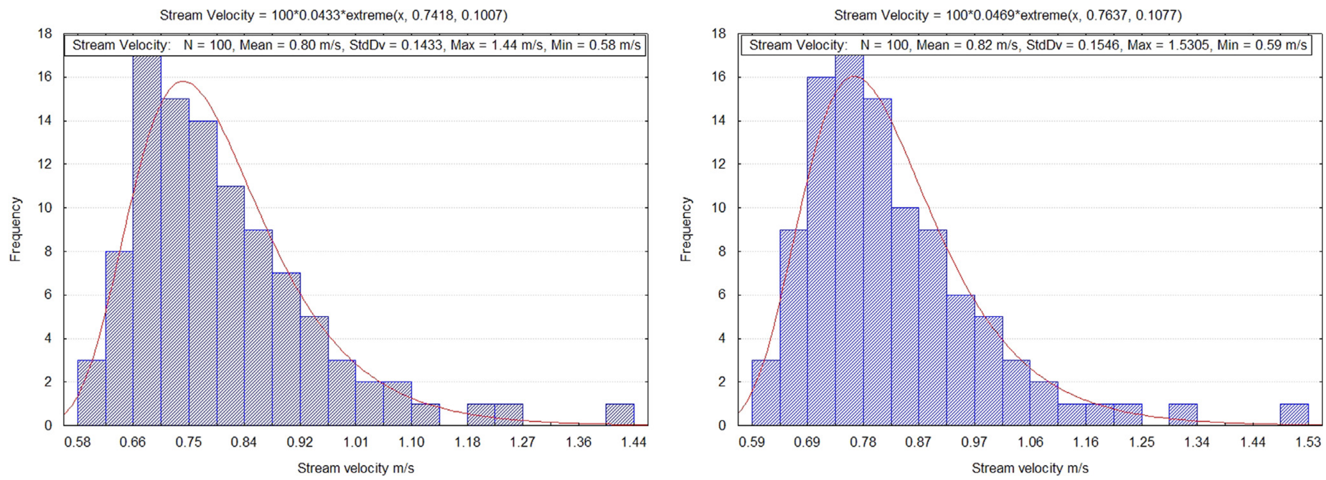

Fig. 14. Mean daily velocity distribution in an average year at the cross-sections of the Nemunas river gauging stations Druskininkai (left) and Nemaniunai (right). Curves indicate theoretical distribution functions [34].

drought. For computations it is reasonable to use a velocity histogram (Fig. 14), which helps optimise the solution and avoid gross errors.

Our investigations resulted in the development of a new compact mobile converter of river kinetic energy for use in a lowland river [35]. The construction of the first prototype is ongoing.

7. Adjustment of the river flow for the conversion of kinetic energy

It has been mentioned above that the water flow geometric parameters and velocities vary in the river flow cross section and in time within broad limits [33,34]. This peculiarity should be carefully considered when the rated depth and velocity of the flow are determined. These parameters are used for selection of the converter type and its design.

The stream and the concentration of velocities at definite part of the cross section area are rather seldom observed. Usually the flow is evenly distributed along the cross section, while some streams happen to be present there.

The magnitude of the river flow local velocity varies from zero at the bed surface to maximal in the middle of the river close to the flow free surface. The velocity varies with time in a hardly predictable order. They receive maximal magnitudes during the short flood period and drop to minimal during the long drought season.

Dissipation of river flow kinetic energy in both the cross section areas along the river and the time makes the extraction of energy complicated. Histograms of water flow velocities (Fig. 14) are very useful for determining the optimal rate.

Our studies of Lithuanian rivers resulted in the development of a special river flow management system [36]. This makes it possible to collect the water flow into a small part of the cross section area thereby concentrating the water discharge and increasing the flow velocity. It helps a lot to increase the efficiency of kinetic energy extraction from the river flow.

8. Conclusions

1. The resources of kinetic energy in lowland river streams are small, and the conditions of their development are difficult; therefore careful estimation of the feasibility of developing these resources should be conducted prior to taking the design and construction work.
2. The insufficient velocities of the flow and limited resources of kinetic energy the lowland rivers containing water vegetation and suspended particles in water channels require special in-stream energy converters and technologies for their practical application.
3. The insufficient depths of lowland rivers make conveyer-type converters most suitable for utilisation of their kinetic energy. Due to the presence of aqua-plant fibres and concentration of hard and high suspended sediments in the channel of lowland rivers the converters should contain a small number of moving elements and friction couples.

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